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MATTER TO THE DEEPEST: Recent Developments
in Physics of Fundamental Interactions,
USTROŃ'09

Tests of the Standard Model with Early LHC Data

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ATLAS

CMS
Compact Muon Solenoid

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Outline

Status of LHC

ATLAS and CMS

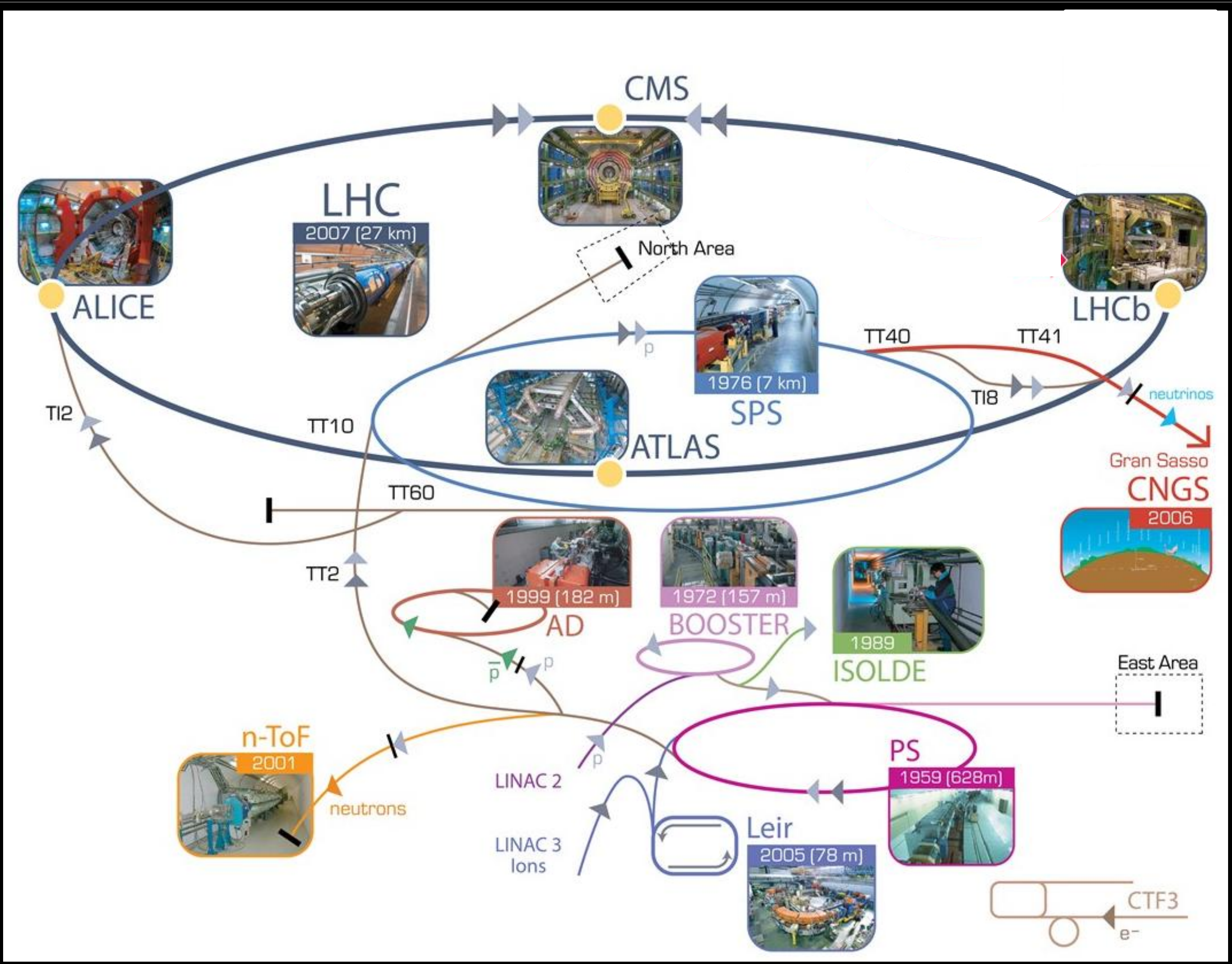
QCD physics

B physics

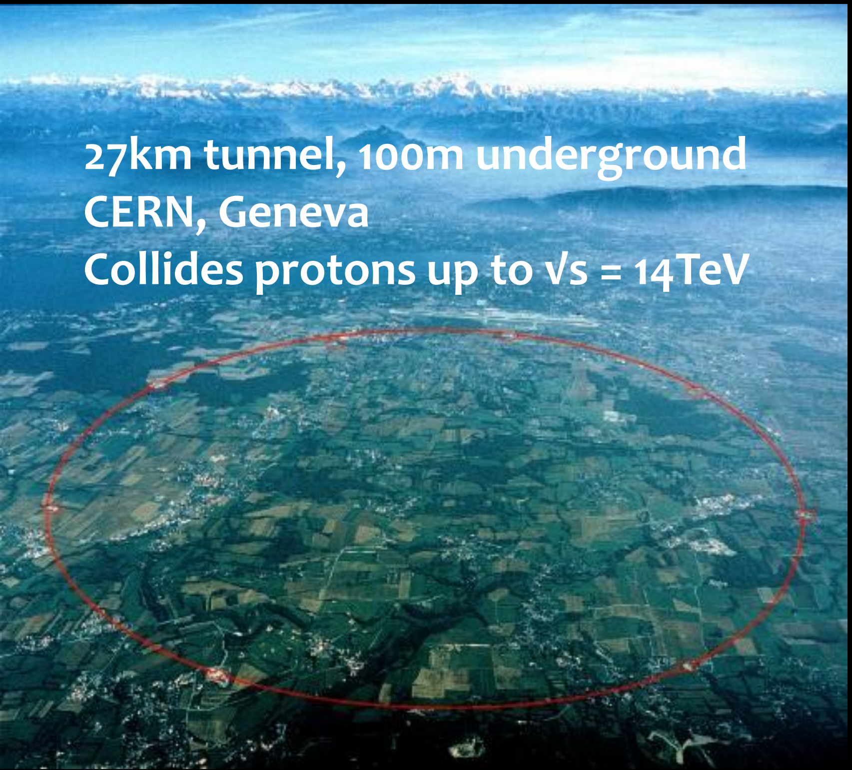
W and Z physics

Top quarks

CERN accelerator complex



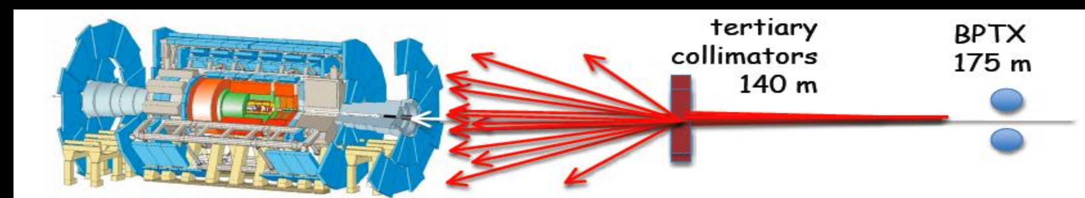
The LHC machine



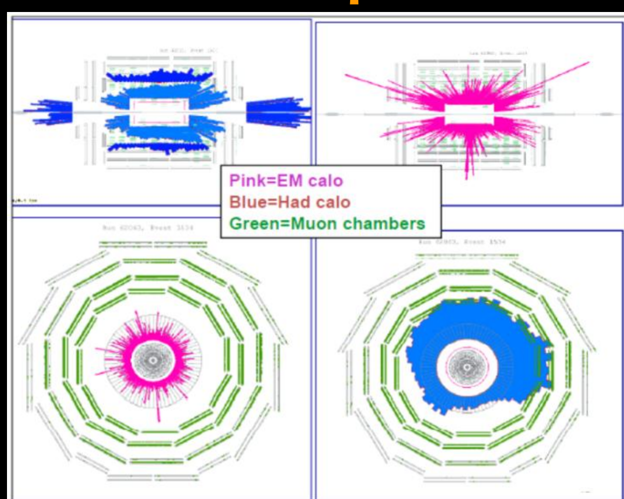
- **1232 high-tech superconducting dipole magnets**
  - Magnetic field: 8.33 T
  - Operation temperature: 1.9 K (pressurized superfluid helium)
  - Dipole current: 11.85 kA, stored energy: 7 MJ
  - Dipole weight: 34 tons
  - 7600 km of Nb-Ti superconducting cable

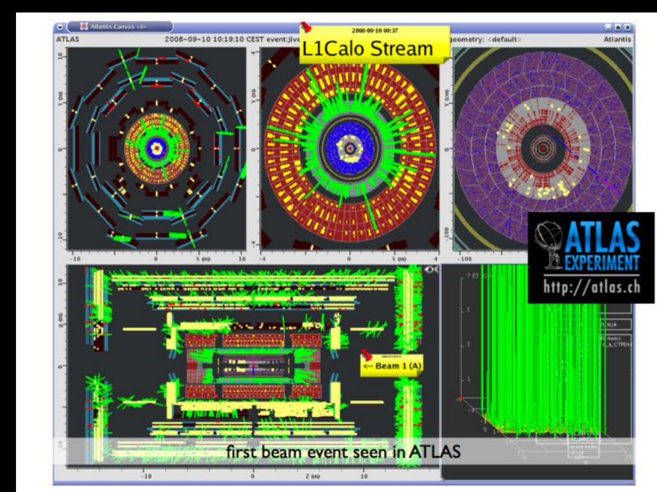
First beams on September 10^{th} 2008

- Spectacular start of the LHC
  - At 10^{30} beam 1 around the ring, makes 3 turns
  - At 15^{00} beam 2 around the ring, 3-4 turns
  - At 22^{00} beam 2 circulates for hundreds of turns



- Both detectors ready
  - Record beam-splash events, beams collide with collimators

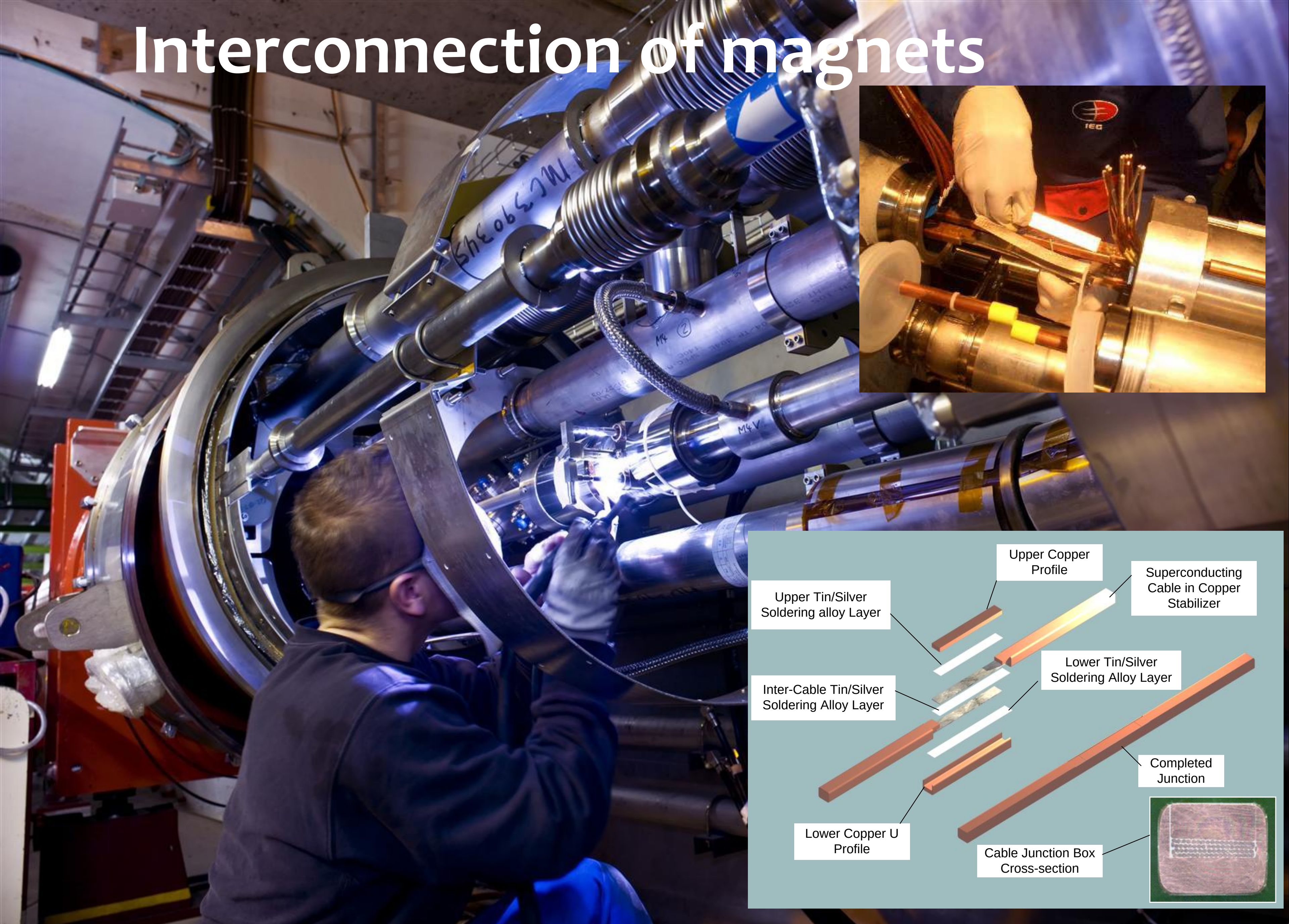




The 19th September accident

- During powering tests in Sector 3-4, LHC down time
  - Electrical fault producing electrical arc
  - Significant mechanical and electrical damage over 700m
  - Release of He from magnet cold mass
  - Contamination of vacuum
- At 8.7 kA (~ 5.1 TeV), a resistive zone appeared in the superconducting busbar between quadrupole Q24 and the neighboring dipole
  - Specified <0.6 nΩ, average <0.2 nΩ
  - In cell 24R3-25R3 ~ 220 nΩ measured (post-mortem)
  - bad welding 'splice'

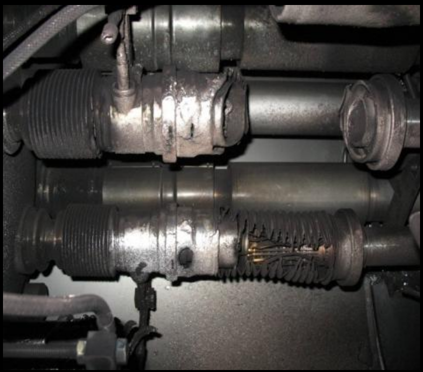
Interconnection of magnets



Collateral damage

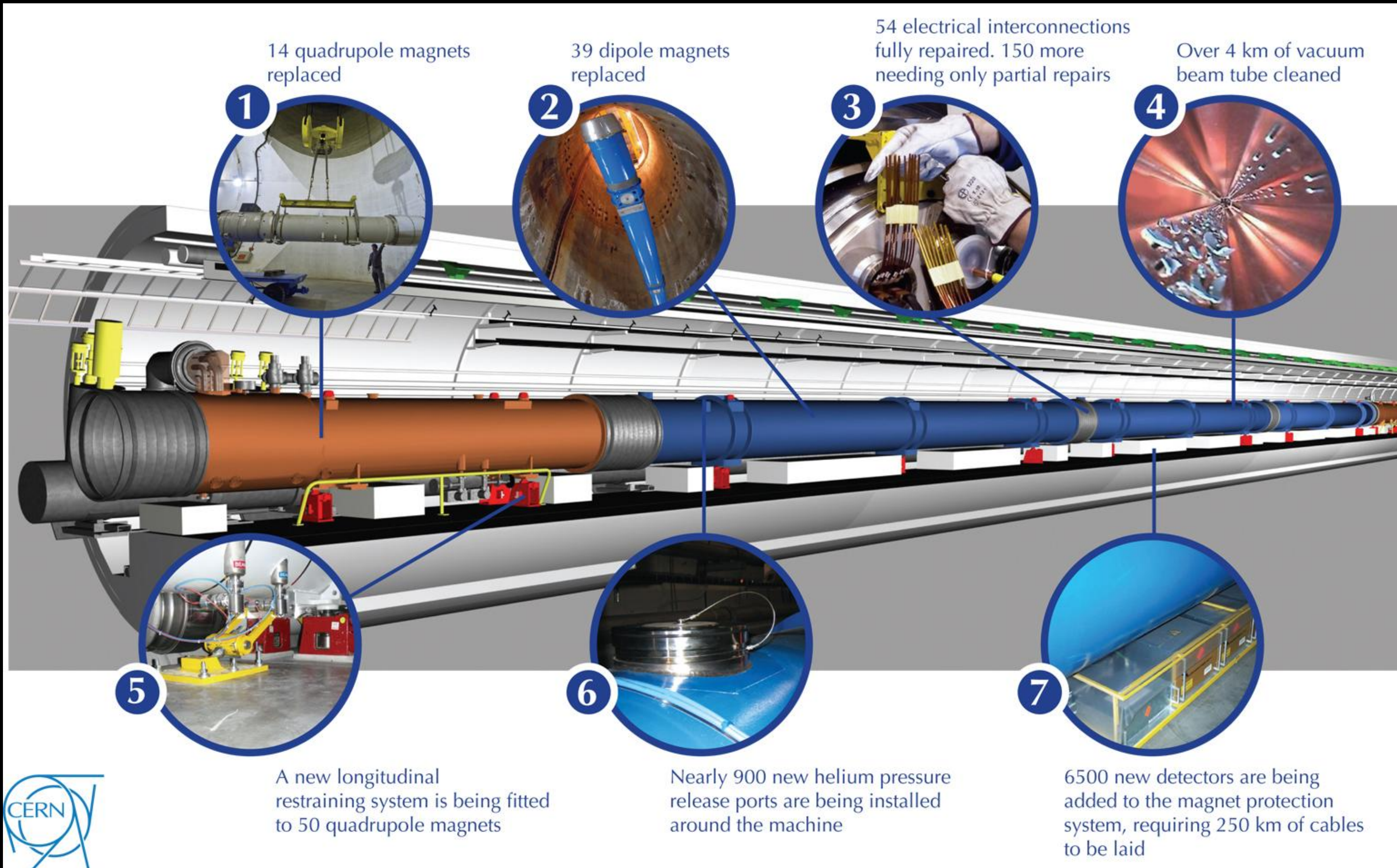
- Electric arc between dipole C24 and quadrupole Q24
  - > 4MW dissipated after one second
  - Helium enclosure punctured
  - Fast discharge of helium into insulation vacuum (2 tons)
  - Large pressure resulted in longitudinal displacement up to tens of cm

Heat of electrical arcs melted 375kg of Copper (equivalent)



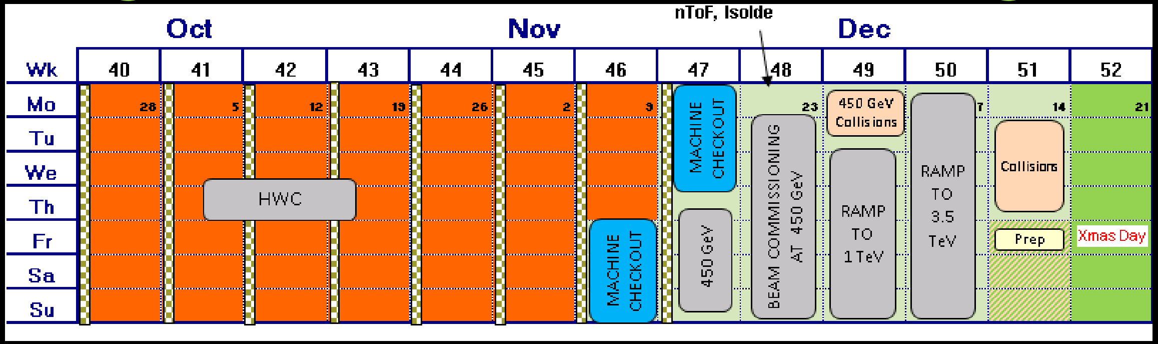
Supporting jacks

The LHC repairs in detail



LHC schedule

- Information updated on
  - http://lhc-commissioning.web.cern.ch/lhc-commissioning/
- Current best guess (M. Lamont, Aug 2009)



  - 2009
    - Start collisions at 900GeV in November 2009
    - Ramp up to 7TeV before 12days Christmas shutdown
  - 2010
    - Possibly run three months at 7TeV
    - Run 5 months at 8-10TeV
    - One month heavy ions
- Most recent simulation studies performed at 10TeV

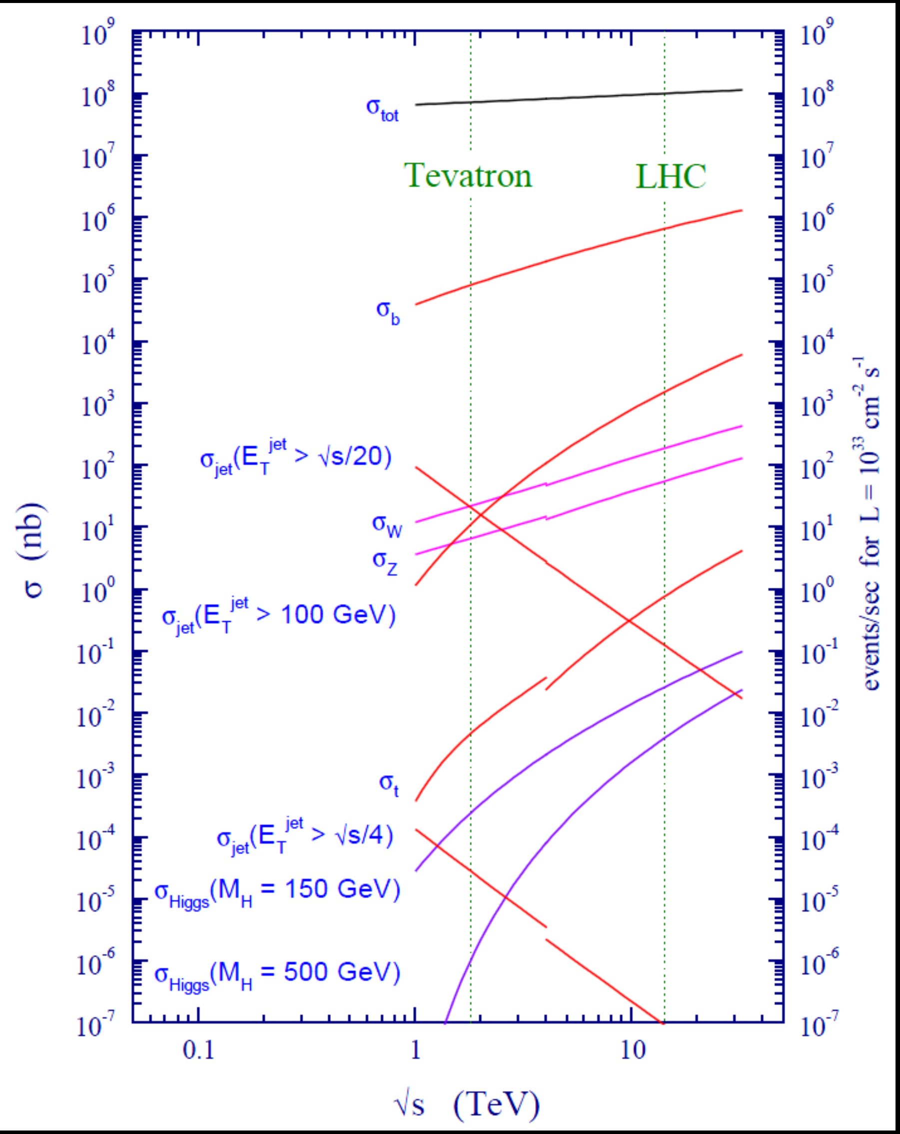
What is discussed in this talk

- **NOT discussed**
  - initial LHC "engineering" runs at $\sqrt{s}$ = 900 GeV (injection energy)
  - very low luminosities (< 10^{30} cm^{-2} s^{-1})
  - pre-calibrations, cosmic runs

- **Instead I will present physics**
  - at $\sqrt{s}$ = 10-14 TeV for instantaneous luminosities in the range 10^{30}-10^{32} cm^{-2} s^{-1}
  - for integrated luminosities << 1 fb^{-1}
  - in the two general purpose detectors ATLAS and CMS

In summary: EARLY MEASUREMENTS AT THE LHC

Cross-sections and events at LHC

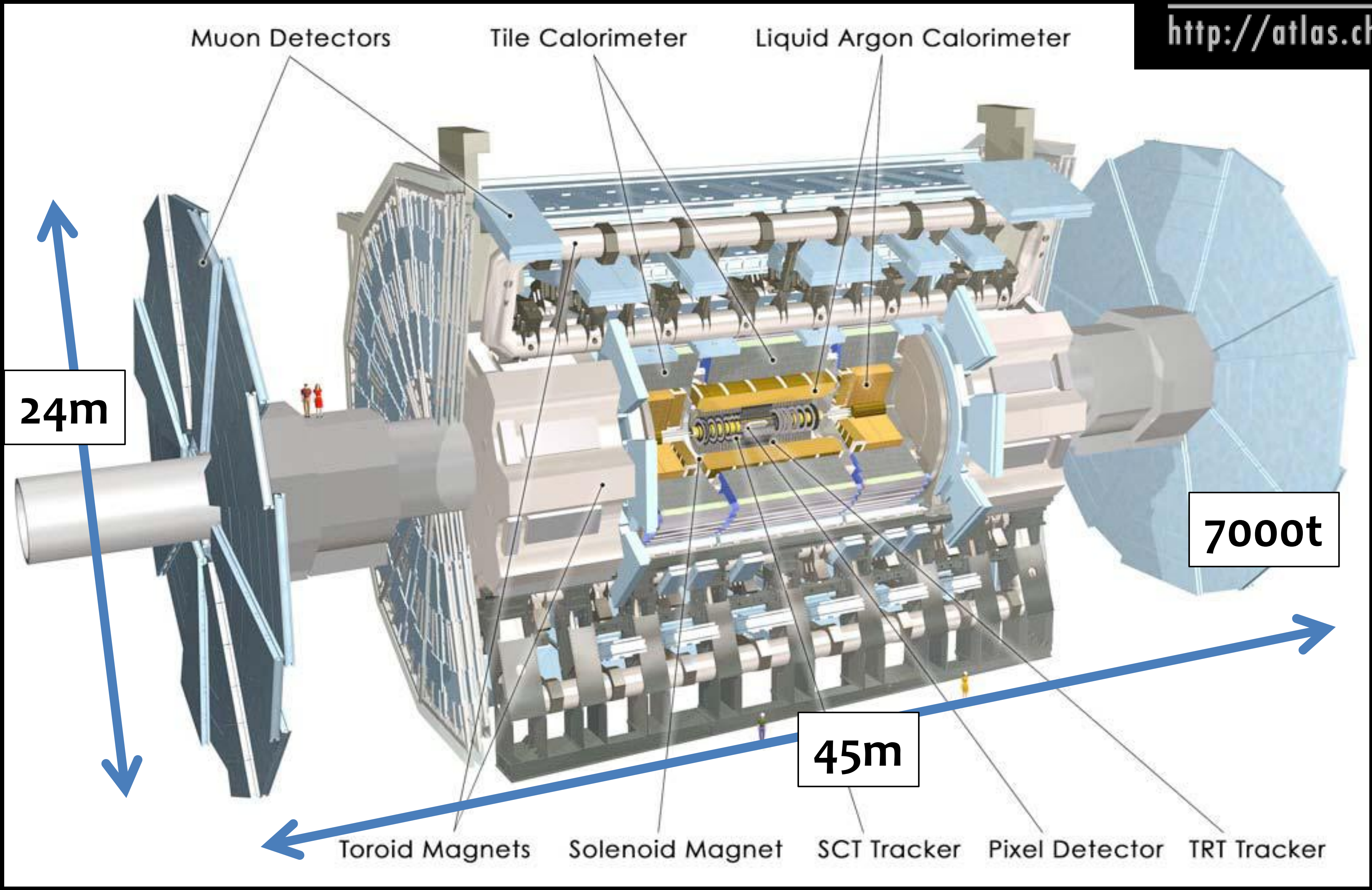


- Interesting physics is hidden beneath a large total cross-section
- Trigger strategies need careful thinking

- Expected selected events per 50 pb^{-1}

Channel	7 TeV	10 TeV	14 TeV
$J/\psi \to \mu\mu$	400k	600k	1100k
$W \to \mu\nu$	110k	150k	200k
$Z \to ee$	13k	18k	25k
$tt \to l$+jets	400	700	1500

A general purpose detector

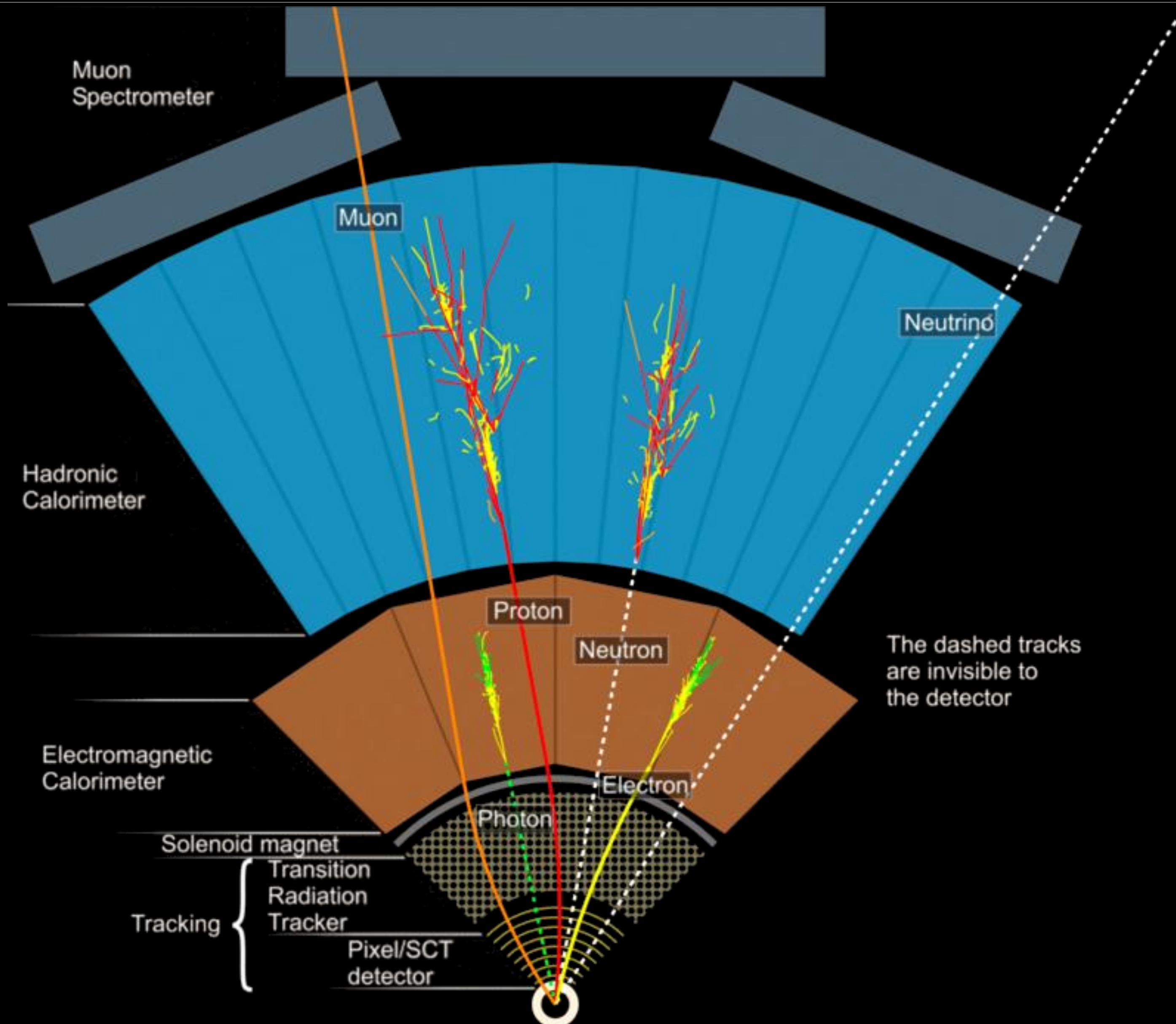


Performance Overview

	ATLAS	CMS
INNER TRACKER	• Silicon pixels + strips • TRT with particle identification • B = 2T • **$\sigma(p_T)$ ~ 3.8%** (at 100 GeV, η = 0)	• Silicon pixels + strips • No dedicated particle identification • B = 3.8T • **$\sigma(p_T)$ ~ 1.5%** (at 100 GeV, η = 0)
MAGNETS	• Solenoid + Air-core muon toroids • Calorimeters outside field • 4 magnets	• Solenoid • Calorimeters inside field • 1 magnet
EM CALORIMETER	• Pb / Liquid argon accordion • **$\sigma(E)$ ~ 10–12% / $\sqrt{E}$ $\oplus$ 0.2–0.35%** • Uniform longitudinal segmentation • Saturation at ~ 3 TeV	• $PbWO_4$ scintillation crystals • **$\sigma(E)$ ~ 3–5.5% / $\sqrt{E}$ $\oplus$ 0.5%** • No longitudinal segmentation • Saturation at 1.7 TeV
HAD CALORIMETER	• Fe / Scint. & Cu-liquid argon • **$\sigma(E)$ ~ 45% / $\sqrt{E}$ $\oplus$ 1.3%** (Barrel)	• Brass / scintillator • **$\sigma(E)$ ~ 100% / $\sqrt{E}$ $\oplus$ 8%** (Barrel)
MUON	• Monitored drift tubes + CSC (fwd) • **$\sigma(p_T)$ ~ 10.5 / 10.4%** (1 TeV, η = 0) (standalone / combined with tracker)	• Drift tubes + CSC (fwd) • **$\sigma(p_T)$ ~ 13 / 4.5%** (1 TeV, η = 0) (standalone / combined with tracker)

Source: Froidevaux-Sphicas, Ann Rev 56, 375 (2006)

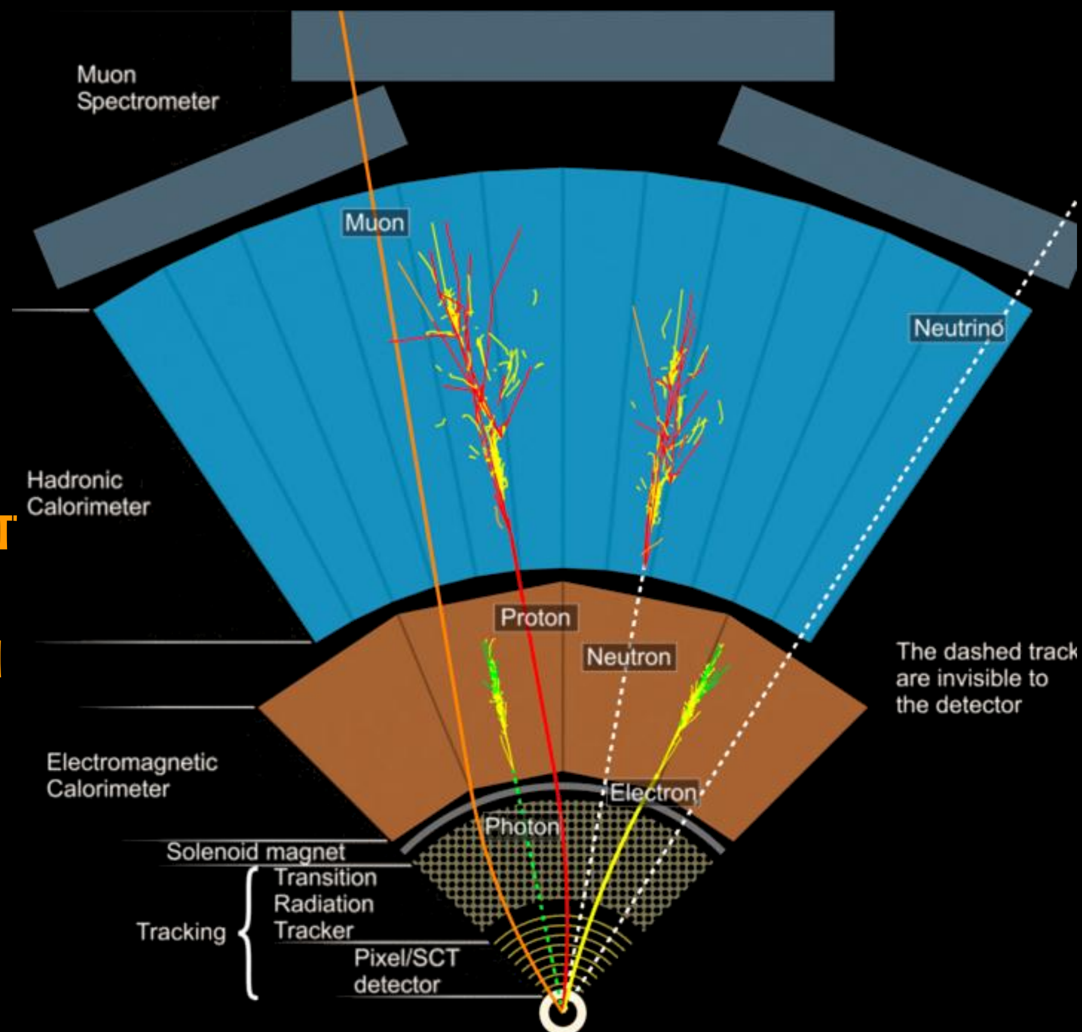
Object reconstruction



e/γ reconstruction

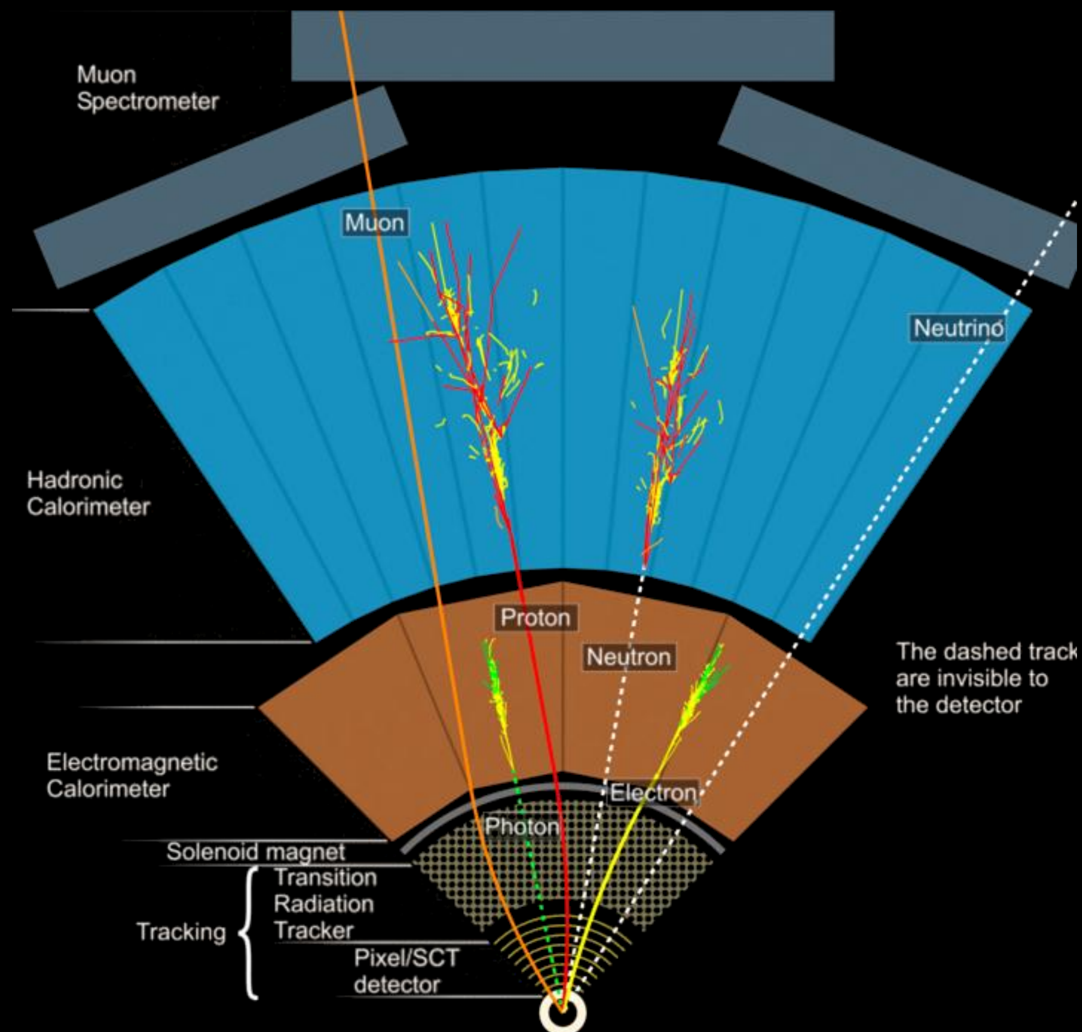
combine information from calorimeters and tracking

- narrow clusters in EM calorimeter, all energy deposited
- e (γ) clusters must (not) match with incoming track
- e can be separated from pions using transition radiation in TRT (ATLAS)
- e's and γ's are typically isolated from other particles
- However, not so for
  - e's from charm and beauty decays
  - γ's from π^0 decays
- Backgrounds stem mostly from misidentified jets



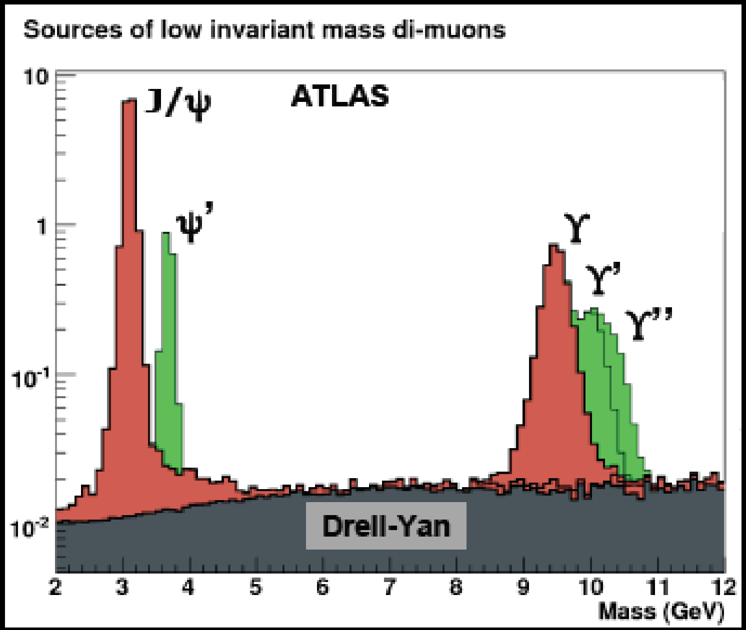
μ identification

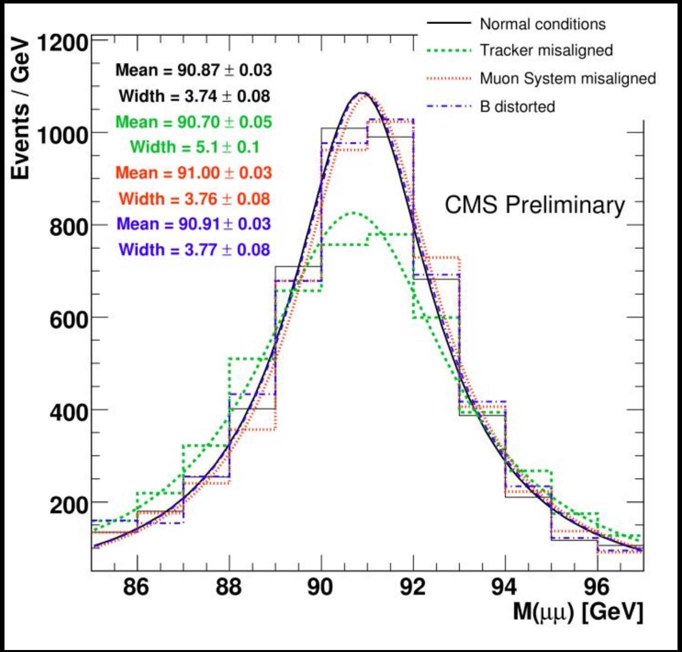
- identified using muon chambers at outer detector (other particles are absorbed)
  - μ momentum and charge can be determined from track bending in B field of muon chambers
  - Backgrounds stem mostly from charged π/K decays in flight



Understand dimuon events

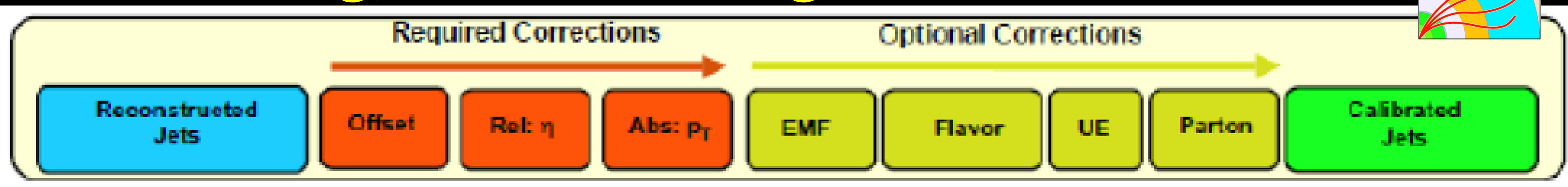
- Thousands of di-muons from J/ψ and Υ for 1 pb^{-1}, hundreds from Z.
- First opportunity to understand tracking and muon resolutions as a function of p_T
  - multiple scattering, alignment distortions, magnetic field uncertainties, …





Jet reconstruction

- # high p_T jets/pb^{-1} at LHC much larger than Tevatron
  - At 10TeV there are $O(10^5)$ jets/pb^{-1} with p_T>200 GeV
    - 320jets/pb^{-1} with p_T>0.5TeV
    - 50dijets/pb^{-1} with m_{jj}>1.4TeV
- Jet reconstruction
  - Cone (seeded, seedless, iterative), (Anti)k_T algorithms
- Jet energy calibration, e.g. at CMS



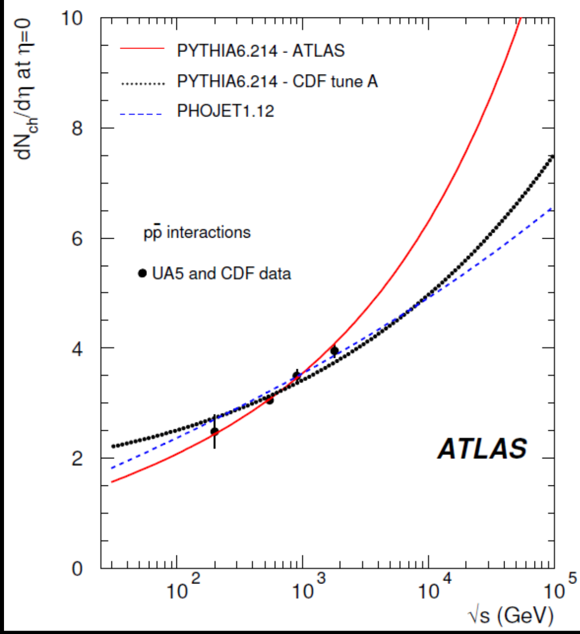
  - Factorized approach: offset, relative and absolute correction
  - Data driven: dijet, γ+jet, Z+jet balancing
  - Systematic uncertainty expect ~10% at startup

Physics menu with very 1st collisions

- Goal: prepare for high-p_T physics and discoveries
  - calibrate detector
  - tune software to LHC physics
  - understand physics of soft hadron interactions
- Minimum bias (MB) events
  - σ_{NSD} (14 TeV) ~ 70 mb (~70% of the total cross section)
  - ~25 MB events superimposed (pile-up) nominal LHC running (10^{34} cm^{-2} s^{-1})
- Underlying event (UE)
  - Everything that is not the hard scattering
- Hadronic event shapes
- B physics

Minimum Bias Events

$\sigma_{nsd} = \sigma_{tot} - \sigma_{elas} - \sigma_{sd} = \sigma_{dd} + \sigma_{nd}$

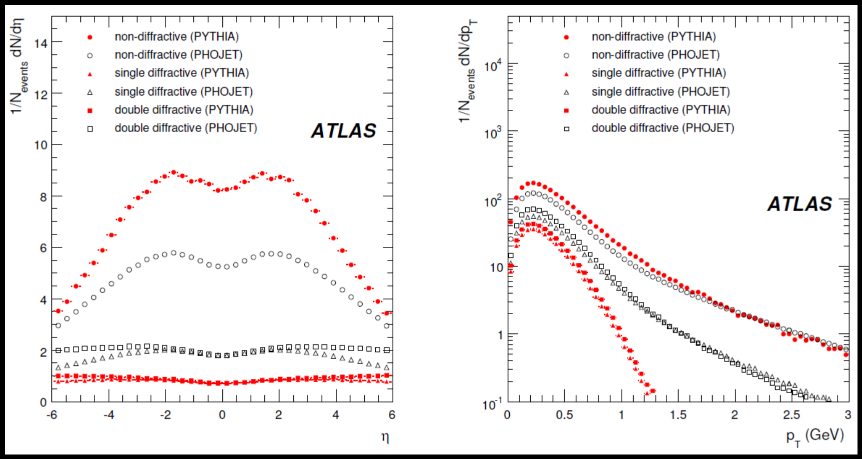


- η and p_T differential distribution of N_{ch}
  - Learn about soft part of underlying event
  - Important to do it early ⟶ avoid pile-up
  - Energy dependence not well constrained
- Backgrounds
  - Beam-gas, beam-halo
- Trigger strategies
  - MB trigger scintillators or random
  - Min # of spacepoints in ID
  - Two tracks (and vertex)
  - SD and DD events selected

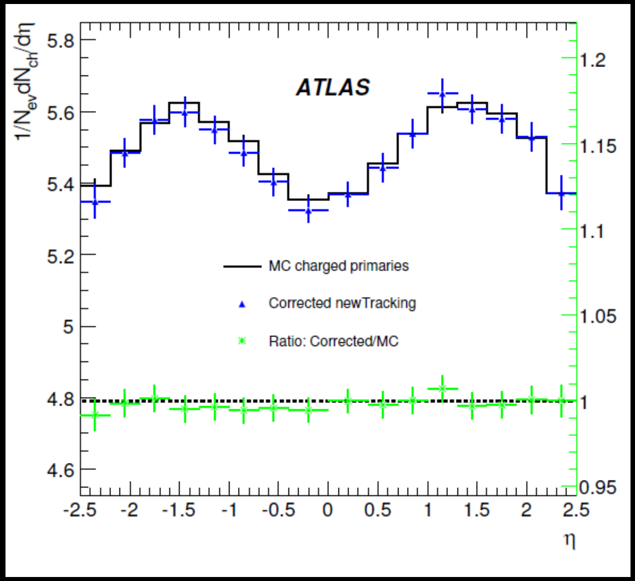
	Cross-section (mb)@14Tev	
Process	PHOJET	PYTHIA
Non-Diff.	69	55
Single Diff.	11	14
Double Diff.	4	10
Central Diff.	1	-
Inelastic	85	79
Elastic	35	23
Total	120	102

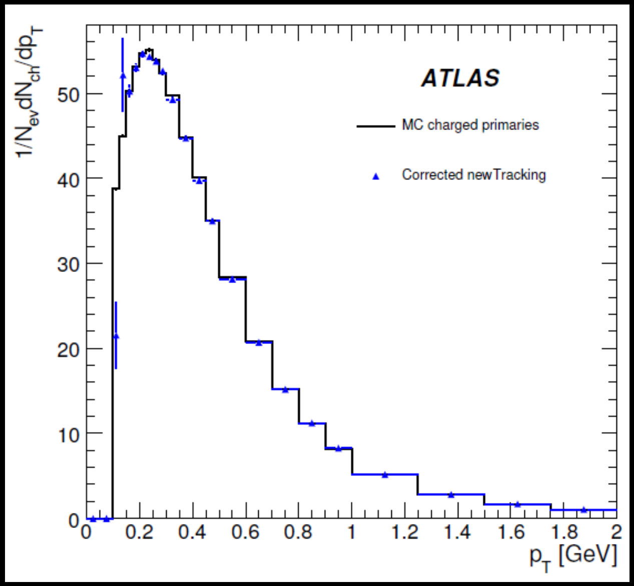
MB differential distributions

Pythia vs Phojet prediction



- Stable charged particles only
- Need to correct for
  - Track-to-particle
  - Vertex reconstruction
  - Trigger bias
- Reconstruction of low-p_T tracks challenging

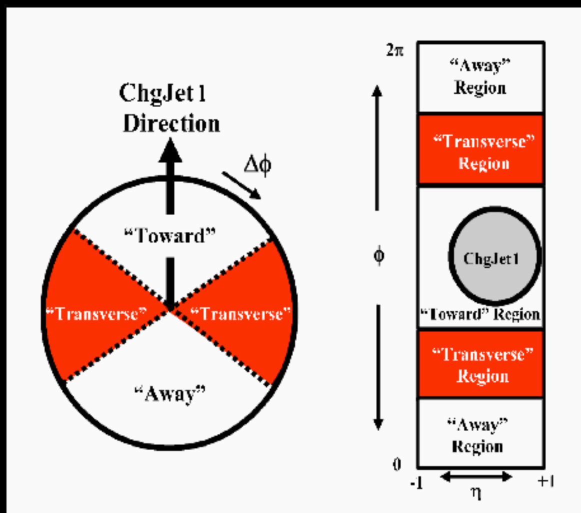


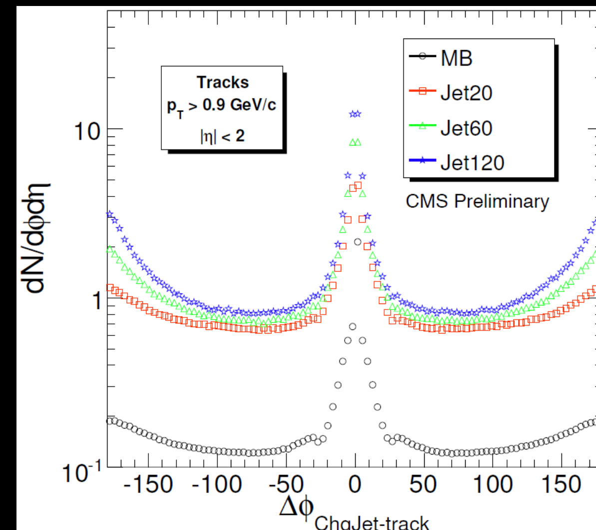


- Systematics
  - Misalignment
  - NSD xsection
  - Composition
  - Trk selection

Understand the underlying event

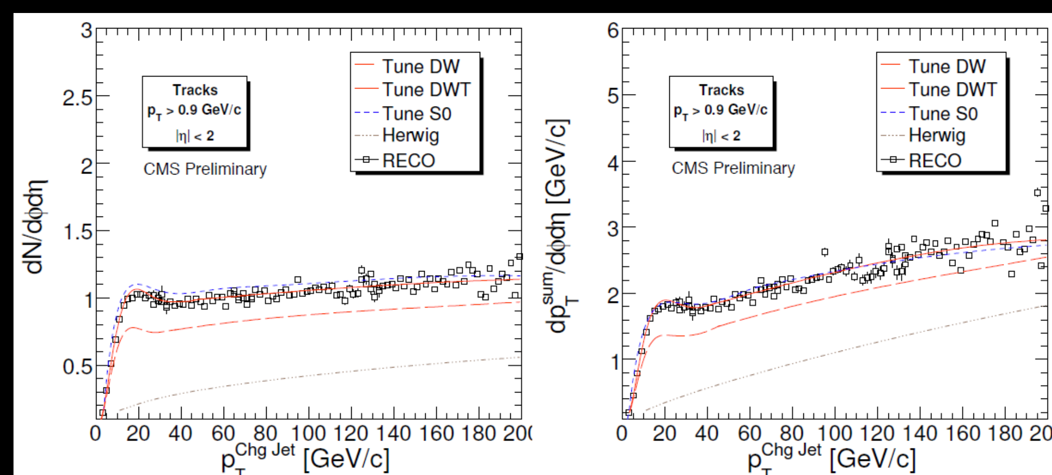
- Underlying activity mainly affects the transverse region of the event





CMS PAS QCD-07-003

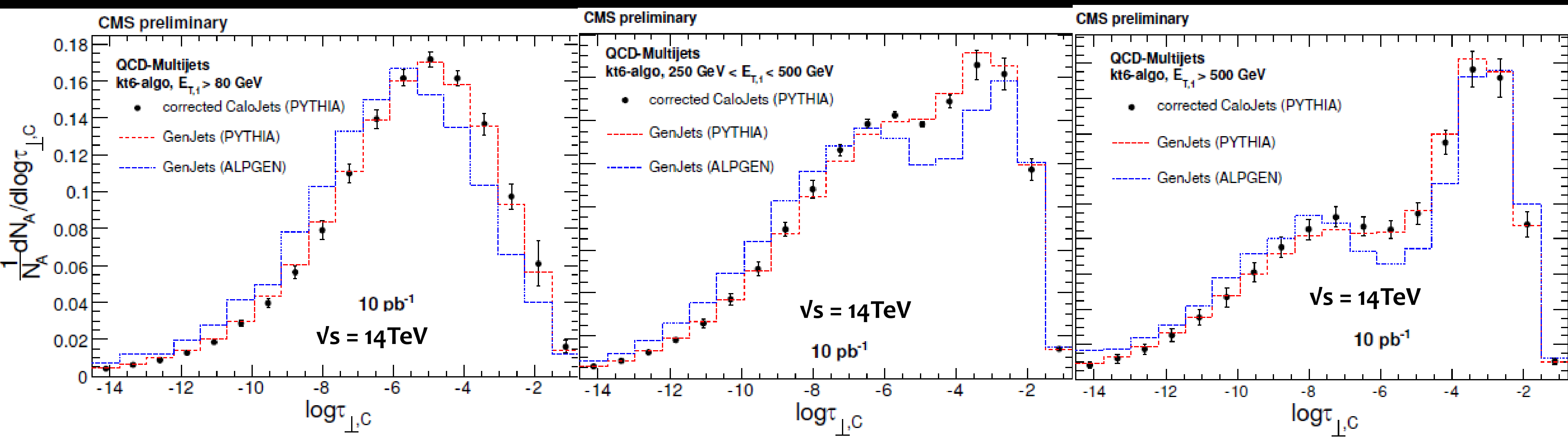
- Density of tracks and p_T in transverse region
  - Extracted distributions well matched with input simulation
  - Model sensitivity



Hadronic event shapes

- Defined in terms of 4-momenta of final state objects
- Infrared and collinear safe ⟶ calculable in pQCD
  - e.g. directly global transverse thrust $T_{\perp,g} \equiv \max_{\vec{n}_T} \frac{\sum_i |\vec{p}_{\perp,i} \cdot \vec{n}_T|}{\sum_i p_{\perp,i}}$
- Normalized to total transverse momentum/energy
  - Energy scale dependence should cancel out (resulting 5%)
  - Useful to understand early QCD events and tune MC
- Can distinguish e.g. Pythia vs Alpgen
  - Three jet E_T bins, 10pb^{-1} integrated luminosity

CMS PAS QCD-08-003



B physics with early data

- Require low-p_T muon trigger
  - Select $J/\psi \to \mu\mu$ and discard background from K and π
- Study inclusive J/ψ and Υ production
- Cross-section and lifetime with $10pb^{-1}$ @ 10TeV
  - $B^+ \to J/\psi\ K^+$, $B^0 \to J/\psi\ K^{*0}$ $d\sigma/dp_T(B)$ and proper lifetime
    - Max. likelihood fit in several bins of $p_T(B)$
    - Expect $\tau(B^+)/\tau(B^0)$ to $5\%_{(stat)} + 1\%_{(syst)}$
    - Expect diff. cross section ratio to $<10\%_{(stat)}$

CMS PAS BPH-09-001

- σ_{bb} and $d\sigma/d\Delta\varphi$ in $50pb^{-1}$ @ 10TeV
  - Opening angle between J/ψ and μ
    - Test QCD, tune Monte-Carlo

CMS PAS BPH-08-004

- Further early data topics
  - Radiative χ_c decays, $B^0_s \to J/\psi\ \varphi$, J/ψ and Υ polarisation

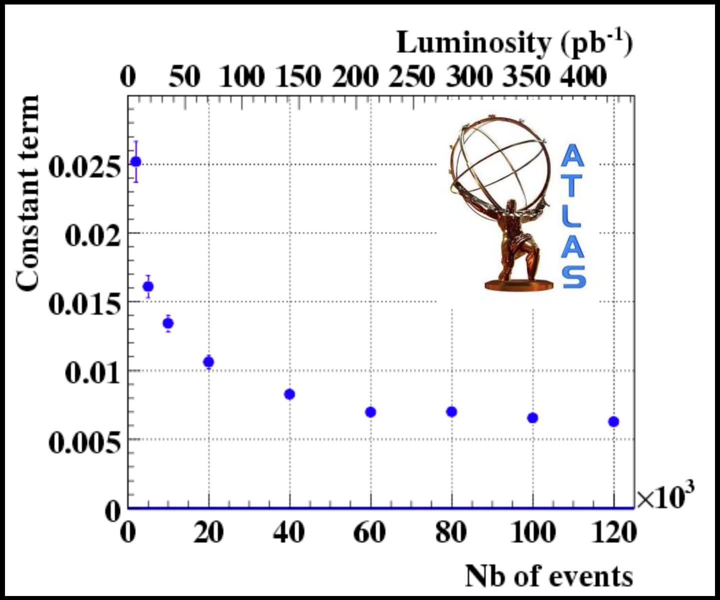
CERN-OPEN-2008-020

Electroweak measurements

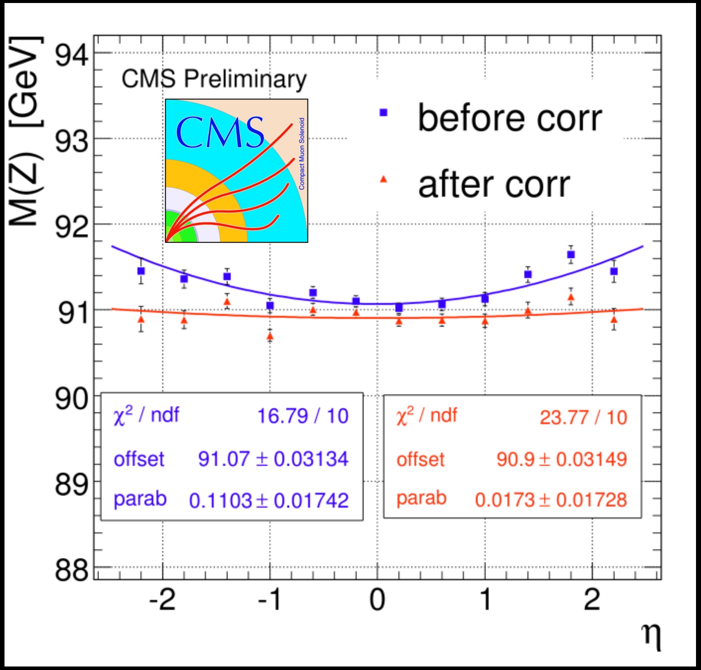
- "Known" physics from previous colliders
  - Unique tool to calibrate the detectors
  - Understand backgrounds for new physics signals
  - Understand detector details and develop tools
    - B-tagging, missing transverse energy, …

$Z \longrightarrow ee$

ECAL intercalibration



muon momentum scale



Electroweak measurements

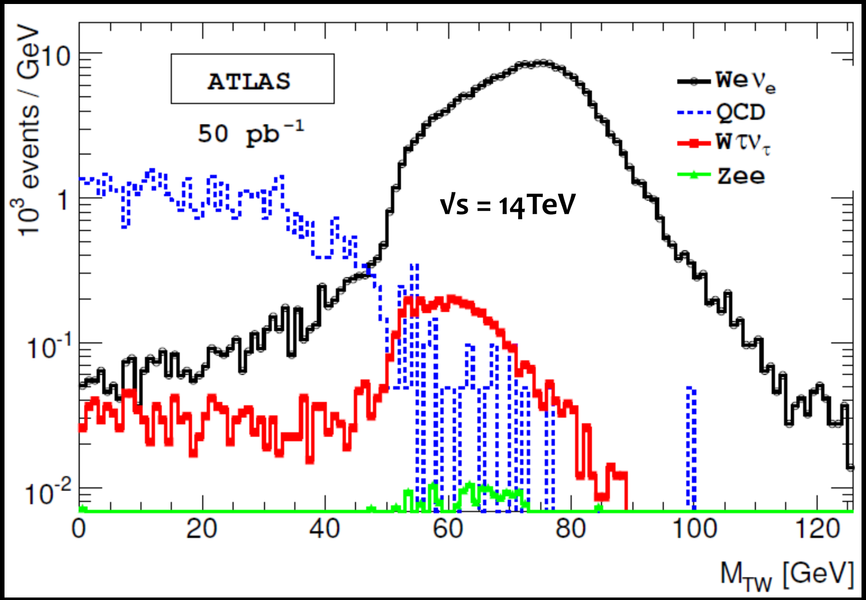
- "Known" physics from previous colliders
  - Unique tool to calibrate the detectors
  - Understand backgrounds for new physics signals
  - Understand detector details and develop tools
    - B-tagging, missing transverse energy, …
- Not so well known after all !
  - higher cm energy, PDF uncertainties (gluons dominate)
- physics channels involving Z, W, γ^*,top production are easily distorted
  - any new physics sources at new energy scales opened up, even with low luminosity!

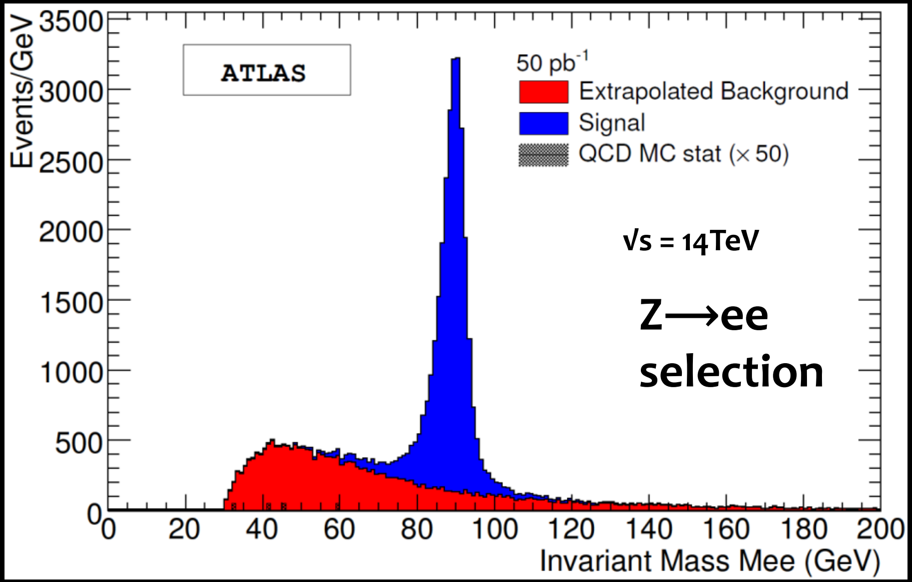
W and Z cross-section

- Theoretical uncertainty of higher order corrections <1%
  - W and Z production stringent test of QCD
    - Differential distributions constrain resummation of initial parton emissions and PDFs of the proton
- Detector calibration with Z
  - Energy scale, resolution, lepton id efficiency
- Electroweak parameters
  - M_W (from W boson decay distribution)
  - $\sin^2\theta_W$ (NC A_{FB})
  - Lepton universality
- Backgrounds:
  - W/Z decaying to τ's, top-pair production,
  - inclusive jet events with fake leptons,
  - low-mass Drell-Yan, diboson events

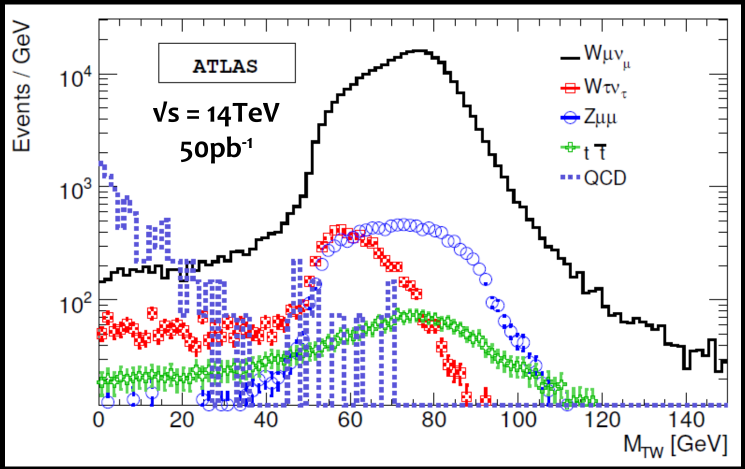
W and Z cross-section with electrons

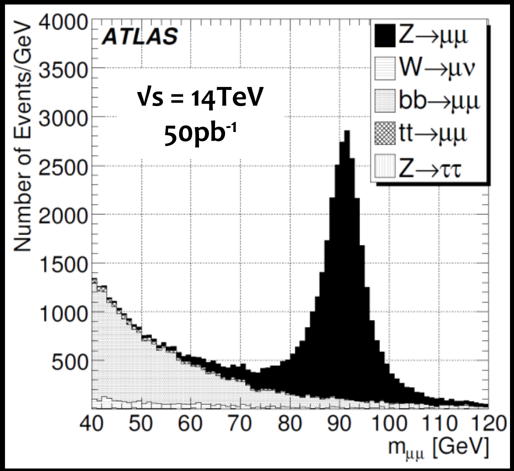
- Assume 10^{31} $cm^{-2}s^{-1}$ trigger menu and $50pb^{-1}$
- $W \rightarrow e\nu$ and $Z \rightarrow ee$
  - Expect 200k and 25k events
  - High E_T electron, MET, M_T (l, ν) or isolation+M(ll)
- Jet events important bckg
  - Normalization uncertainty
  - Data-driven background subtraction before MET cut
  - Select photons instead of electrons





W and Z cross-section with muons



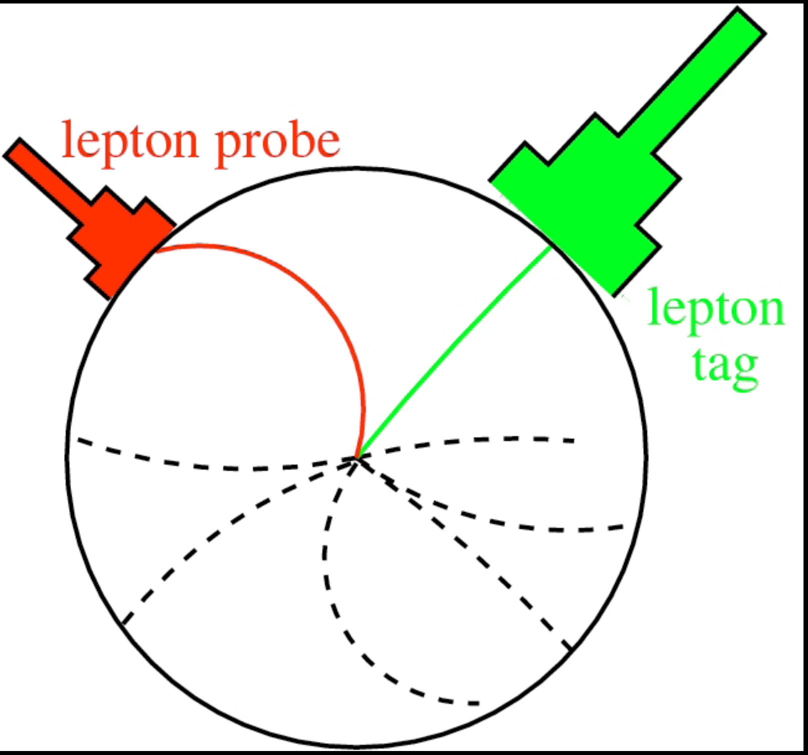


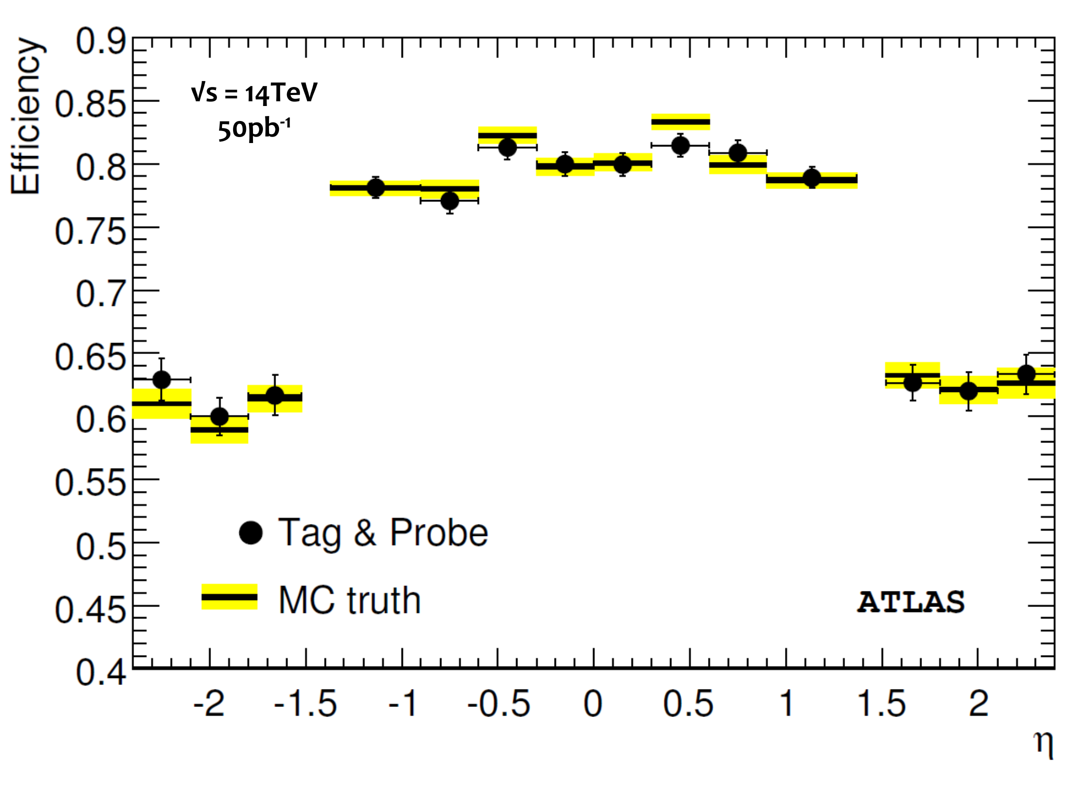
- Analysis with muons in final state
  - ttbar major background
  - Jet events less serious
    - contribution from semi-leptonic b decays
- Systematic uncertainties (excl. luminosity)
  - Efficiency ~2%
  - Acceptance (ISR, PDF, UE, …) ⟶ differential distributions

$\Delta\sigma/\sigma$ ($W \longrightarrow l\nu$) = 0.2% (stat) + 3-5% (syst) $\Delta\sigma/\sigma$ ($Z \longrightarrow ll$) = 0.8% + 4%

Tag and probe

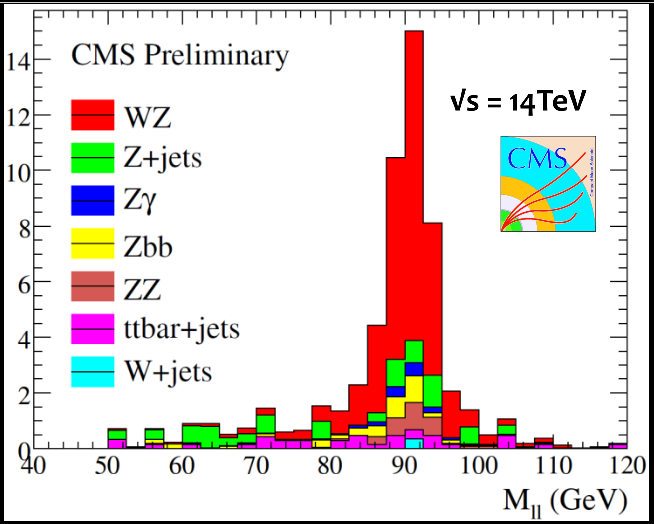
- Extract trigger and lepton reconstruction efficiency
  - Purely data driven
  - E.g. Z→ ll decays





Diboson production and TGC

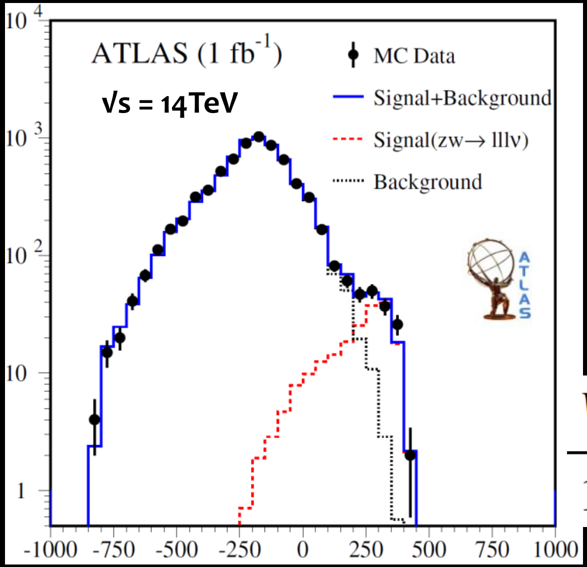
- Important background for new process
  - E.g. H->WW
- Test Standard Model
  - constraining anomalous TGC
- WZ production observable early on
  - 5σ discovery possible at √s = 14TeV with 350pb⁻¹ (CMS)
  - With BDT ATLAS expects >5σ with 100pb⁻¹



CMS PAS EWK-08-003

14TeV 300pb⁻¹

WZ^0	34.9±0.5
$Z^0 + jets$	3.9±1.0
bbll	2.9±0.3
$t\bar{t} + jets$	2.2±0.6
$W + jets$	0.4±0.4
Z^0Z^0	2.8±0.3
$Z^0 + \gamma$	1.4±0.1
Total non genuine Z^0 bkg	2.6±0.7
Total genuine Z^0 instrumental bkg	6.8 ±1.0
Total genuine Z^0 physics bkg	4.2 ± 0.3



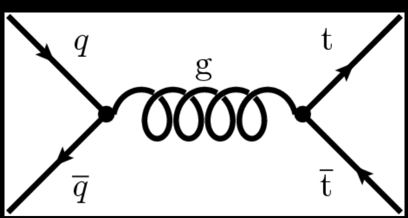
Selected events in 1fb⁻¹
CERN-OPEN-2008-020

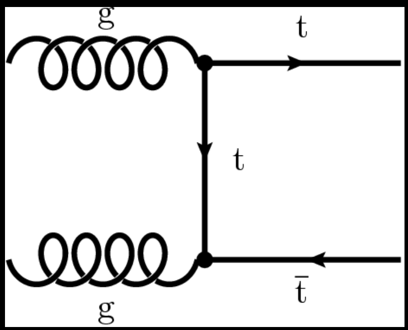
WZ	ZZ	$t\bar{t}$	$Z+$jet	$Z+\gamma$	Other	Total bkg	N_{WZ}/N_B
128	7.7	2.8	2.5	2.0	1.1	**16**	7.9

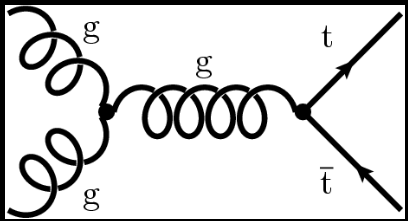
Top physics

- **Abundant in 14 TeV collisions: ~1 pair/sec at 10^{33} cm^{-2} s^{-1}**
  - **Reduced at 10TeV or 7 TeV, still significant**

Strong: ~ 900 pb







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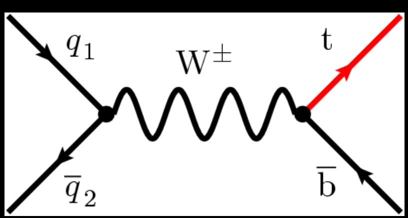
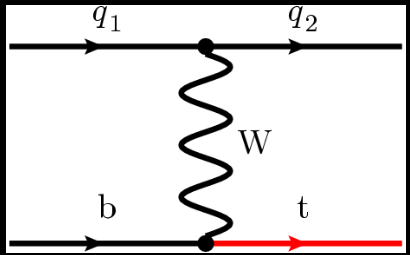
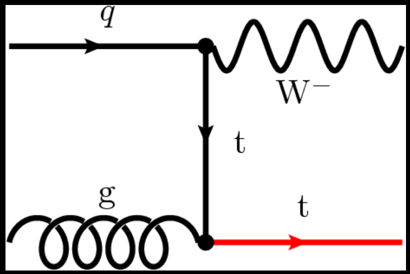
electroweak: ~ 320 pb

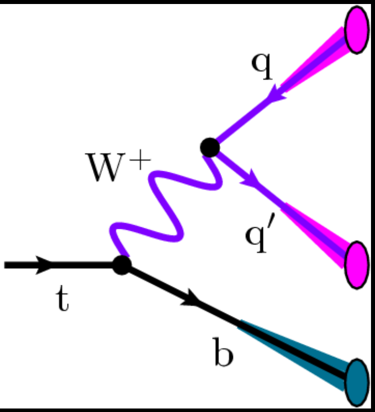






Single top

Top reconstruction



Hadronic (BR ≈ ⅔)

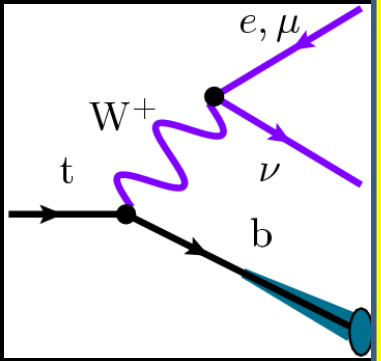
+ can fully reconstruct W and top momenta

- faked by QCD multi-jets (esp. heavy flavor)

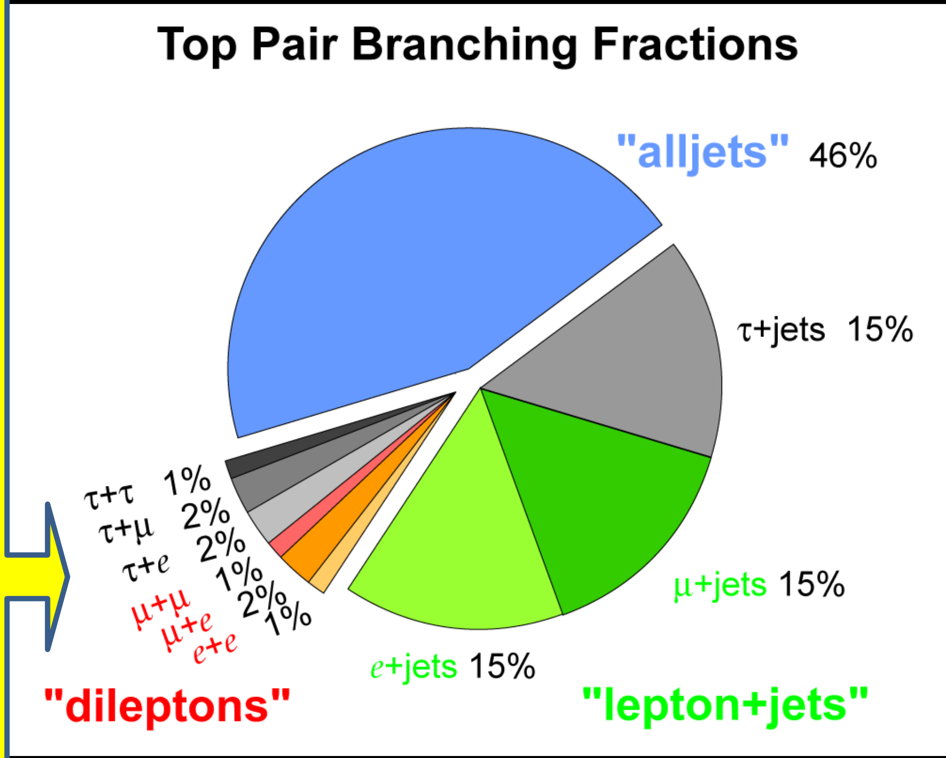
Leptonic (BR ≈ ⅓)

+ Lepton indicates W's charge, helicity

+ Reject QCD via lepton and missing E_T



- Kinematic info (partly) lost

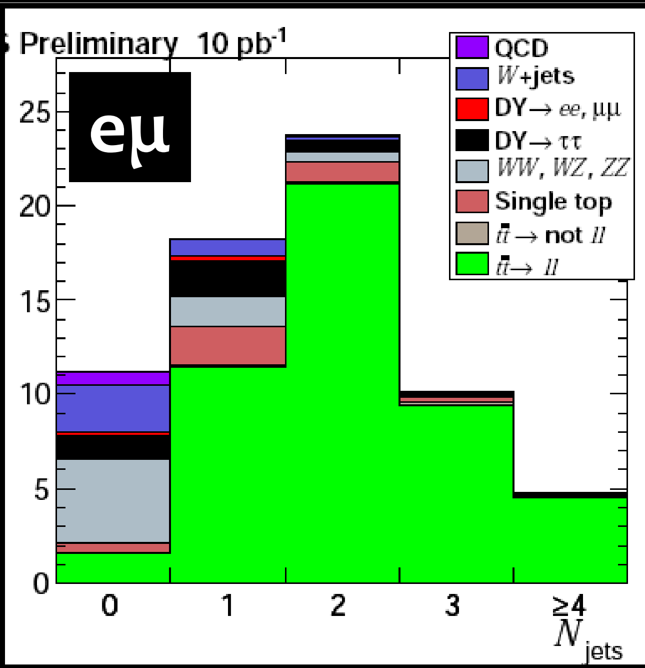


- σ(tt) will validate
  - Lepton identification
  - Jets/missing E_T
  - B-tagging

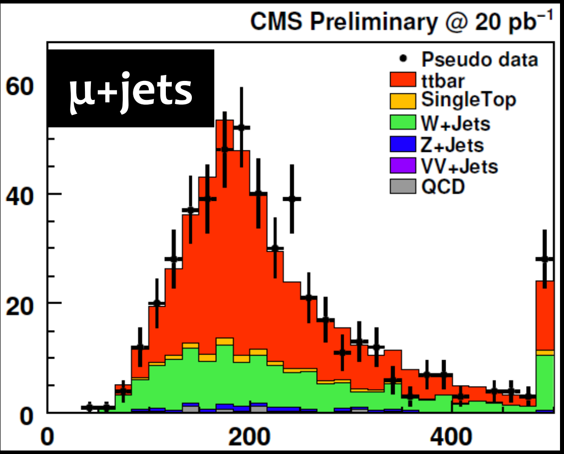
Top rediscovery in tt at 10TeV

- Dilepton channel, $10pb^{-1}$ (eμ S/B ~ 9)
  - 2 OS leptons, MET>30GeV, ≥2jets
  - Combined $\Delta\sigma/\sigma = 15\%_{(stat)} + 10\%_{(syst)}$+lumi

CMS PAS TOP-09-002, -003, -004



- Lepton+jets $20pb^{-1}$



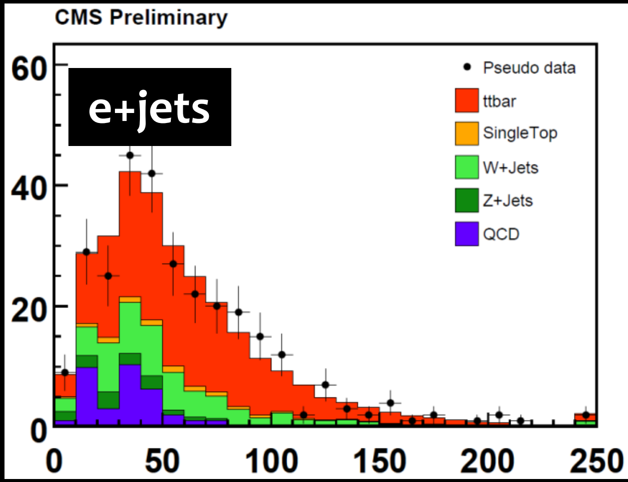
M_3(GeV)

Muon+jets S/B = 1.8

- Template fit to M_3 or η(μ)
- $\Delta\sigma/\sigma = 12\%_{(stat)} + 19\%_{(syst)}$+lumi

Electron+jets, S/B=1.6

- $\Delta\sigma/\sigma = 23\%_{(stat)} + 20\%_{(syst)}$+lum

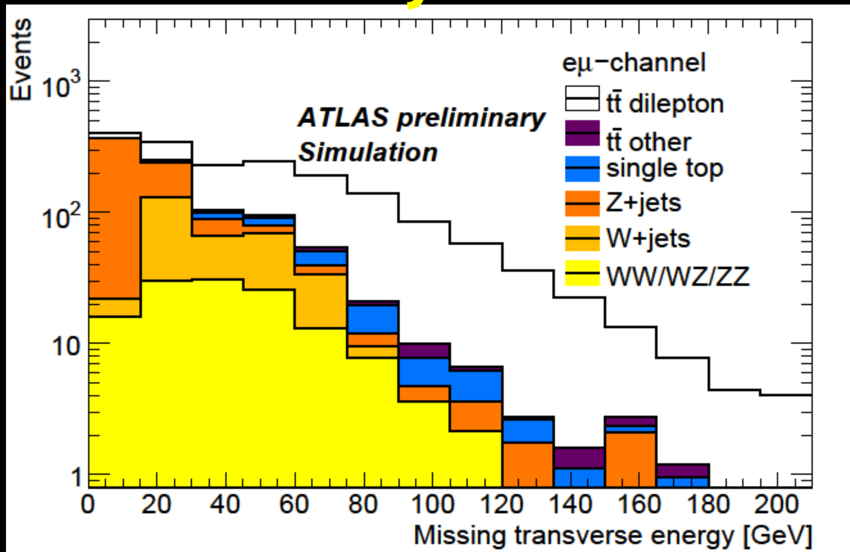


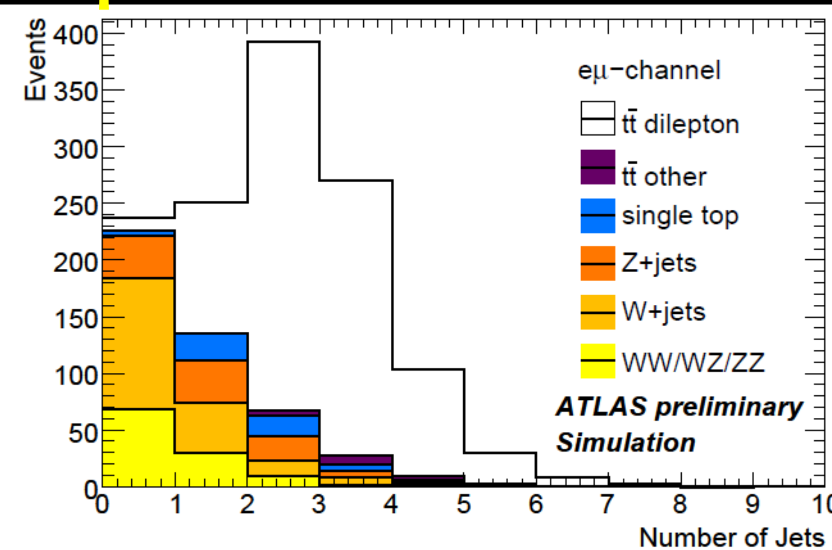
MET(GeV)

Top quark dilepton

ATL-PHYS-PUB-2009-086

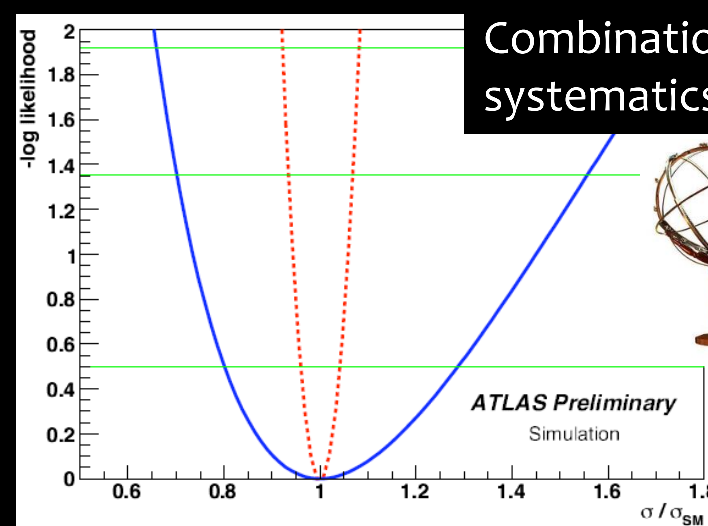
- ATLAS study for 10TeV at 200pb^{-1} → 1200 selected evts





$\Delta\sigma/\sigma$ (%)	ee channel	$\mu\mu$ channel	$e\mu$ channel	combined
Stat only	-7.5 / 7.8	-6.0 / 6.2	-4.0 / 4.1	-3.1 / 3.1
Luminosity	-17.3 / 26.3	-17.4 / 26.2	-17.4 / 26.2	-17.4 / 26.2
Electron Efficiency	-4.5 / 5.0	0.0 / 0.0	-2.2 / 2.4	-1.9 / 1.9
Muon Efficiency	0.0 / 0.0	-4.6 / 5.2	-2.1 / 2.2	-2.2 / 2.3
Lepton Energy Scale	-0.3 / 1.6	-2.4 / 2.0	-0.5 / 0.5	-0.8 / 0.8
Jet Energy Scale	-3.4 / 3.2	-3.0 / 4.5	-2.5 / 2.5	-2.8 / 3.0
PDF	-2.1 / 2.3	-1.4 / 1.6	-1.6 / 1.8	-1.7 / 1.8
ISR FSR	-4.0 / 4.2	-3.6 / 3.7	-3.5 / 3.5	-3.6 / 3.7
Signal Generator	-4.7 / 5.4	-4.6 / 5.4	-4.7 / 5.3	-4.7 / 5.3
Cross-Sections	-0.3 / 0.3	-0.3 / 0.3	-0.3 / 0.3	-0.3 / 0.3
Drell Yan	-1.4 / 1.3	-2.2 / 2.2	-0.5 / 0.5	-0.8 / 0.9
Fake Rate	-9.7 / 9.5	-1.1 / 1.1	-6.2 / 6.2	-4.0 / 4.0
All syst but Luminosity	-12.7 / 13.9	-8.9 / 10.2	-9.4 / 10.2	-8.7 / 9.6
All systematics	-21.0 / 30.3	-19.3 / 28.3	-19.5 / 28.5	-19.3 / 28.1
Stat + Syst	-22.3 / 31.3	-20.2 / 29.0	-19.9 / 28.8	-19.5 / 28.3

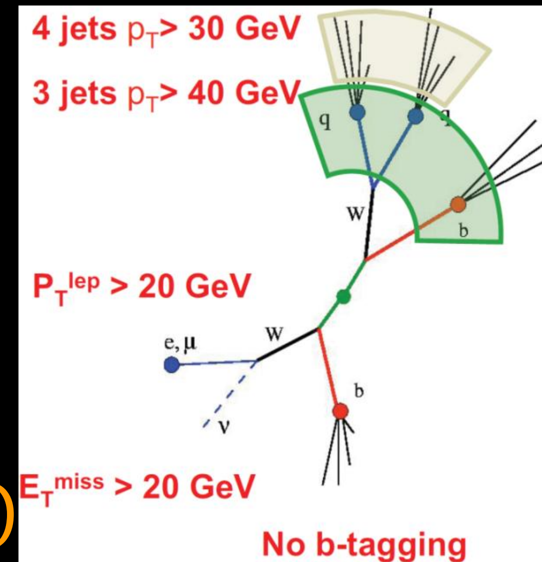
Combination of systematics

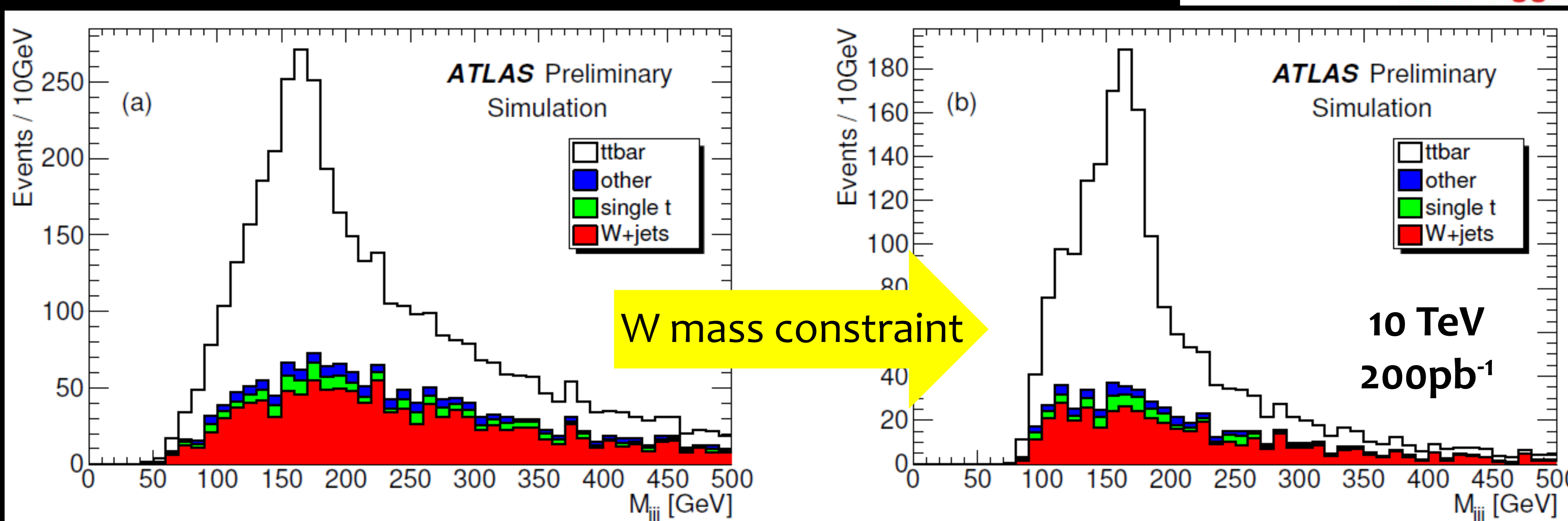


Top quark lepton+jets

ATL-PHYS-PUB-2009-087

- Standard object selection, no b-tag
- Cut-and-count or likelihood fit
  - S/B ~ 2 for e and μ channel
- Exercised in different flavors
  - $\Delta\sigma/\sigma = 3\%_{(stat)} + <15\%_{(syst)}$ +lumi
  - $\Delta\sigma/\sigma = 3\text{-}6\%_{(stat)} + 15\text{-}20\%_{(syst)}$ +lumi (w/o MET)

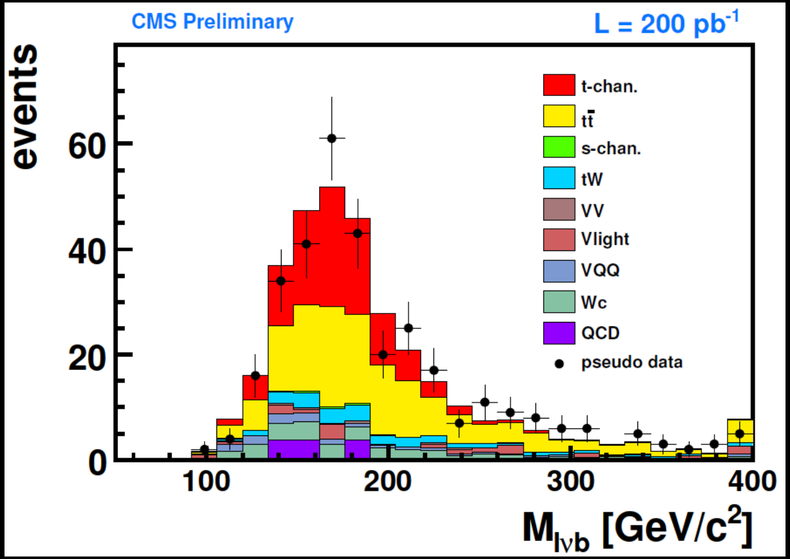


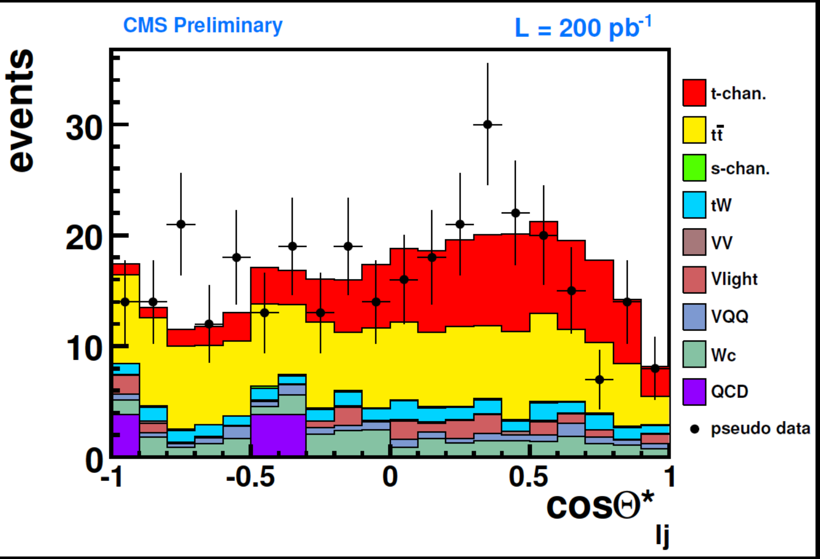


Single top

- Evidence in t-channel expected with 200pb^{-1}@10TeV
- Select single-top events against QCD, tt and W+jets
- Top is 100% polarized ⟶ further discrimination
- Measure σ(single-top) with uncertainties
  - 35%(stat) +14%(syst) +10%(lumi)

CMS PAS TOP-09-005

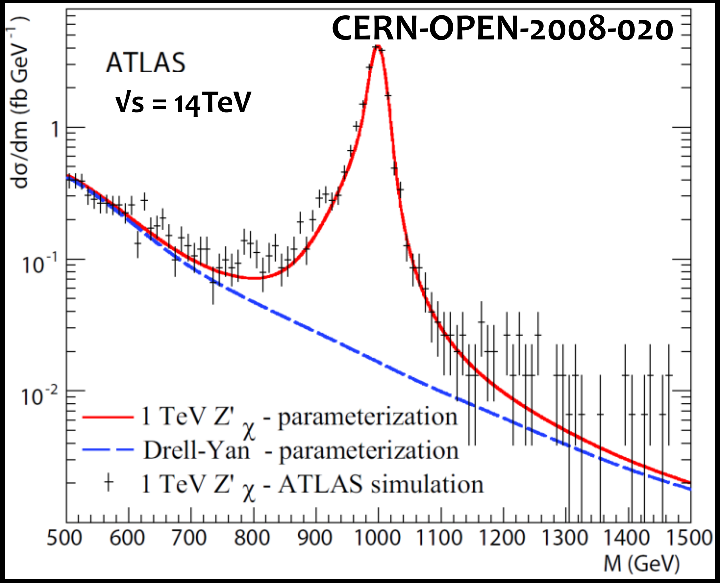




- Possible improvement: charge asymmetry in pp collisions

Z' search

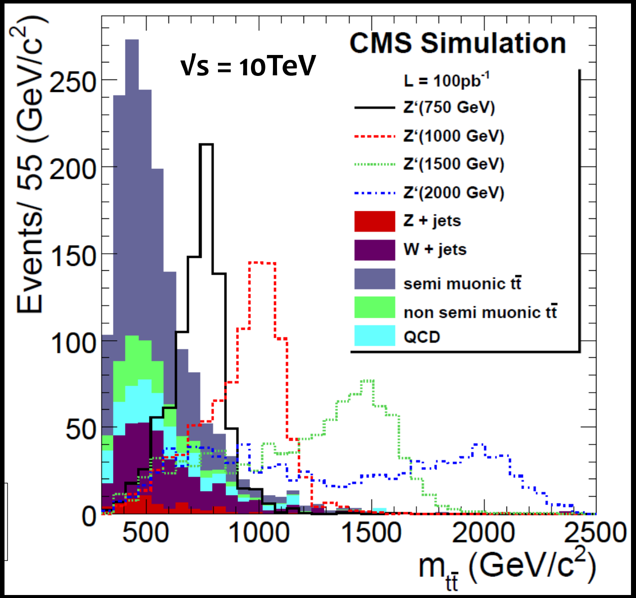
- Search for heavy resonance decaying to a lepton pair
  - With 100 pb^{-1} large enough signal for discovery up to m > 1 TeV
  - Signal is (narrow) mass peak on top of small Drell-Yan background
  - Ultimate calorimeter performance not needed

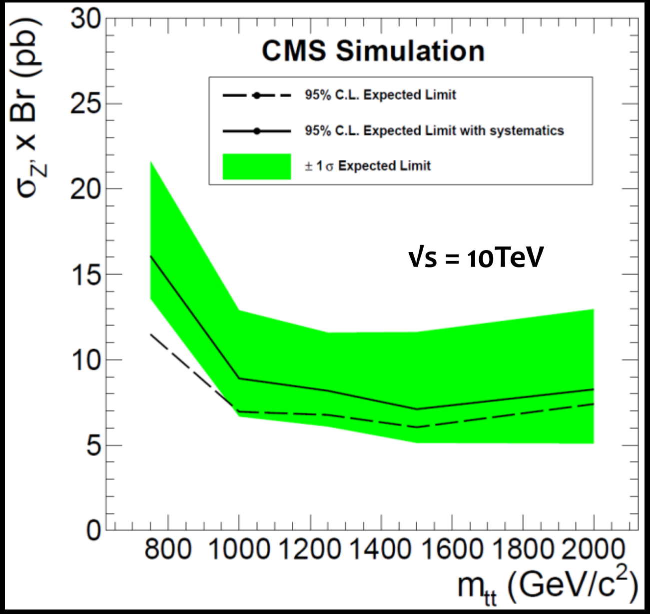


- … decaying to a top pair
  - Kinematic fit in events w/ μ
  - Up to ~2TeV

CMS PAS TOP-09-009

ATLAS-PHYS-PUB-2009-087





What changes at lower √s ?

- Plan to run at 14TeV, 10TeV, 7TeV,…
- Reduced cross-sections
  - e.g. ttbar from ~900pb^{-1} to ~400pb^{-1} to ~150pb^{-1}
  - W/Z ~65% (14TeV ⟶ 10TeV)
- Strong reduction of energy reach for high masses and energy scales
  - Z' resonance (m=2TeV) 20%
  - One order of magnitude less reach for new physics effects at scales ≥ 4 TeV
- More subtle effects
  - Less gluon-gluon relative to qqbar hard interactions

Summary

- QCD and EW processes at start-up extremely important
  - Understand detector and validate algorithms
  - Not so well known: PDF uncertainties and new regime
  - Main background for searches
- Sizeable samples with low luminosity
  - $1pb^{-1} \longrightarrow$ jets, W/Z, J/ψ, ϒ
  - $20pb^{-1} \longrightarrow$ top, B
  - $100pb^{-1} \longrightarrow$ W/Z + 4jets
  - $150pb^{-1} \longrightarrow$ dibosons
- LHC experiments are developing strategies and organizing efforts to understand as soon as possible the detectors and the basic QCD/EW processes
- This is critical for the success of the LHC program

References

- Baseline studies (14TeV)
  - The ATLAS Experiment at the CERN Large Hadron Collider, JINST 3 S08003, 2008
  - Expected Performance of the ATLAS Experiment Detector, Trigger and Physics, CERN-OPEN-2008-020; arxiv/0901.0512
  - Physics Performance TDR, CMS Collaboration, CERN/LHCC 2006-021, J. Phys. G: Nucl. Part. Phys. 34 (2007)

- Most recent public studies (incl. Summer'09, 10TeV)
  - ATLAS: https://atlas-physco.web.cern.ch/atlas-physco/ATLASPubNotes.html
  - CMS: https://twiki.cern.ch/twiki/bin/view/CMS/PhysicsResults